Identification of Grouting Discontinuity of Rock Bolts as an Efficient Way to Control Safety Conditions in Mine Roadways

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Abstract

A rock bolt which is grouted underground may not be properly installed with the result being a discontinuity of the resin layer. Such discontinuity may also occur in working conditions due to typical rock behaviour and displacement. It may be very hazardous to mine safety. In this paper an outline of a method for non-destructive identification of a discontinuity of a resin layer surrounding rock bolt is presented. The method uses modal analysis procedures and is based on an impact excitation where a response transducer is positioned at a visible part of a rock bolt. As an installed rock bolt acts as an oscillator, different lengths of discontinuity of resin layer change its modal parameters. By proper extraction of these parameters, from which a resonant frequency is seen as most valuable, the intended identification is possible. The results of identification of resin discontinuities are discussed. Experiments were performed in an experimental coal mine as well as in coal and copper mines. Also the influence of explosions on installed rock bolts is presented.

Key Words

Mine; Rockbolt; Support System; Method; Modal Analysis

Introduction

The function of the rock bolt support system is to anchor and reinforce the rock zone in the near field of an underground opening to deeper rock strata, Li [1]. Predominantly for that purpose steel rock bolts are used, Tadollini [2]. The rock bolt consists of a steel bar grouted in an oversize hole. A portable installation machine is used to spin the bolt into the hole filled with fast setting epoxy resin cartridges. After hardening of the resin a plate and nut is driven up the bolt. Although robust resin cartridges are available in the market, in mining practice the rock bolt is quite frequently not fully encapsulated as a consequence of rock divergence, resin deterioration, escape of grout into crevices, rock strata movement or improper grouting.

In order to verify the proposed method research was performed in an experimental cal mine as well as in existing coal and copper mines. The investigated cases of discontinuity of resin layer may be divided into cases where:

- discontinuity was known before the test,
- discontinuity was unknown before the test,
- discontinuity was known before the test only to the staff of a mine department.

Below the example results of undertaken study are presented.

Description of the Method

The methodology is based on the assumption that boundary conditions have to be such that the in-situ bolt behaves like a cantilever. Different lengths of grouting discontinuity form different boundary conditions and change the modal parameters of an installed rock bolt. Excited modes transfer to the outer part of the rock bolt, which enables measurement of global characteristics. The method, as Staniek [3] described, uses modal analysis procedures and is based on impact excitation. It consists of two main phases: experimental, which entails the measurement of modal characteristics of an investigated object; and theoretical involving the reference to the finite element model databases. To obtain such databases theoretical modal analysis is performed on the FE model of a tested structure and for different border conditions related to different cases of discontinuity. The model includes over 1000 theoretical cases where the change in discontinuity was made with a resolution of 5 cm. The model is scalable to different rock bolt diameters and rock bolt lengths. The parameters of rock and grout i.e. density, Poisson's ratio and Young's modulus were estimated experimentally according to standard methods, Ulusay [4] and EN 1936 [5]. To be used as a reference, the theoretical model demands

refinement in relation to verification of type of border conditions and contacts assumed in FE model, Dossing [6], Ewins [7], Maia [8] and Uhl [9]. That was done taking into account 28 different cases grouted in the experimental coal mine with preset, known discontinuities in the resin layer. To enable in situ investigations a portable measurement system was designed and built. As a programming tool the LabVIEW environment was used, Bishop [10]. Sampling rate was chosen as 16 kHz, which seemed to be sufficient concerning resolution of FRF plots as well as frequency range. Simultaneously, the import of recorded data and derivation of modal parameters were performed utilizing CADA-X [11] modal analysis software. The measurement setup and its application concerned with acquisition and recording of data in real mining conditions is shown in Figures 1, 2a and 2b. After removing the plate and nut, a response transducer (accelerometer) was fixed onto a visible part of a rock bolt, approximately 2 cm from its end. After transverse vibration excitation of the rock bolt, signals from both the force transducer (which is located on the impact hammerhead) and the accelerometer were recorded. To avoid nod points and improve the results through averaging of measured FRF curves the excitation was repeated 5 times and at 4 to 7 points selected at equally spaced intervals of approximately 2 cm each. The accelerometer was mounted using a metal belt and from practical point of view it was quite easy to clamp it onto the end of the rock bolt. Other methods of mounting were also investigated, using wax and magnet. For wax attachment no significant difference was observed. Magnet is not recommended since it does not ensure absolute repeatability and positioning especially in impact testing with the result that coherence is quite poor, Bruel & Kjaer [12].

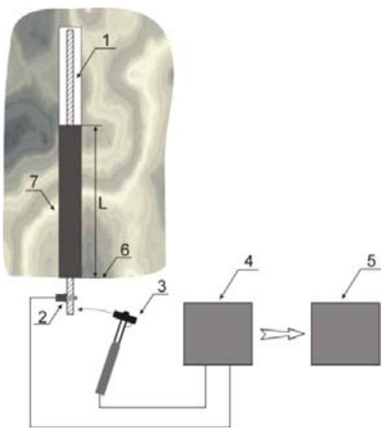


FIG. 1 EXPERIMENTAL SETUP: (1) ROCK BOLT, TYPICAL LENGTH 1.5m – 2.5m; (2) ACCELEROMETER; (3) IMPACT HAMMER; (4) PORTABLE MEASUREMENT SYSTEM; (5) WORKSTATION FOR MODAL ANALYSIS; (6) SURFACE OF UPPER ROOF SECTION; (7) GROUT LAYER - L IS A GROUTED LENGTH

FIG. 2 a: PORTABLE UNIT FOR ACQUISITION AND RECORDING OF FREQUENCY RESPONSE FUNCTION, IN SITU MEASUREMENT

FIG. 2 b: EXCITING A ROCK BOLT WITH AN IMPACT HAMMER, RESPONSE OF THE IMPACT MEASURED WITH PIEZOELECTRIC ACCELEROMETER

Results of Undertaken Study

Research Work in the Experimental Coal Mine „BARBARA" GIG

In this section the results of validity check are discussed. Figures 3a, 3b and 4a, 4b below present example results of research work of a total of 28 rock bolts with different lengths of grouting discontinuity installed in an experimental coal mine. For these cases the process of grouting was controlled at the stage of installation i.e. known discontinuities.

Examples of identified natural frequencies for both the experimental cases and their theoretical counterparts are presented in Tables 1 and 2. The degree of

refinement may be seen by comparing these natural frequencies. For the case presented in Figure 4b and Table 2 these frequencies are 306.9 Hz and 1872.5 Hz, which are characteristic of the outer part of the rock bolt together with 585,2 Hz and 924,4 Hz, which in turn are characteristic of the hidden, not grouted end part of the rock bolt. Although in the theoretical analysis more natural frequencies were calculated, only some of them were observed in the experiments. The explanation for this is that energy which is transported from a vibrating structure to adjacent structures constitutes a loss of the structure's vibrational energy. For a structural component that is in intimate contact with others, energy transfer to adjacent components can contribute considerable damping and generally makes it difficult to measure the component's energy dissipation itself, Remington [13]. Attenuation of vibration may even approach tens of decibels per meter as far as transmission of vibrating signal along the rock bolt is concerned (higher damping for lower frequencies), Beard [14]. Such attenuation makes amplitude of vibrating signal for modes propagating through grout region comparable with noise level and immeasurable; it seemed to be the case with the first two modes in the example above. The other modes were informative enough for the relevant case to enable grouting continuity identification. It must be mentioned, however, that in certain cases there are too few natural frequencies for the evaluation to be performed. Care should be taken while mode matching and in problematic situations FRAC (Frequency Response Assurance Criterion) have to be calculated to obtain correlation and adjustment of experimental and theoretical models. For excitation at point j and response at point k $FRAC_{jk}$ is defined as (1):

$$FRAC_{jk} = \frac{\sum_{i=1}^{L} \left| \left({}_X H_{jk}(\omega_i)\right)\left({}_A H^*_{jk}(\omega_i)\right) \right|^2}{\sum_{i=1}^{L} \left| \left({}_X H_{jk}(\omega_i)\right) \right|^2 \sum_{i=1}^{L} \left| \left({}_A H_{jk}(\omega_i)\right) \right|^2} \tag{1}$$

Where:

${}_X H_{jk}$ – frequency response function for experimental model,

${}_A H_{jk}$ – frequency response function for analytical model,

i=1,L – discrete points for a frequency range

In mode matching of experimental and theoretical models visual comparison of mode shapes for the outer part of a rock bolt might be useful and ought to be performed in every case.

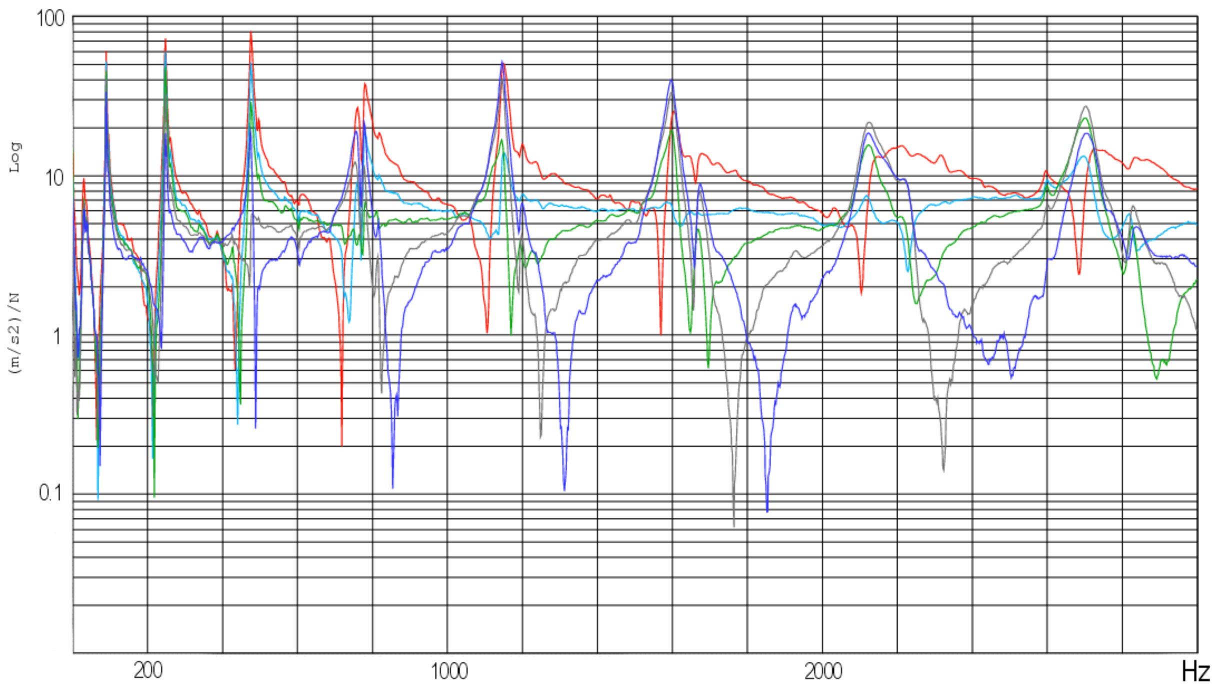


FIG. 3a: FRF CHARACTERISTICS OF DIFFERENT POINTS OF EXCITATION (MARKED WITH DIFFERENT COLORS) FOR A ROCK BOLT GROUTED ON ½ OF ITS LENGTH, STARTING FROM A REAR, HIDDEN END. AXIS X – FREQUENCY, AXIS Y – INERTANCE

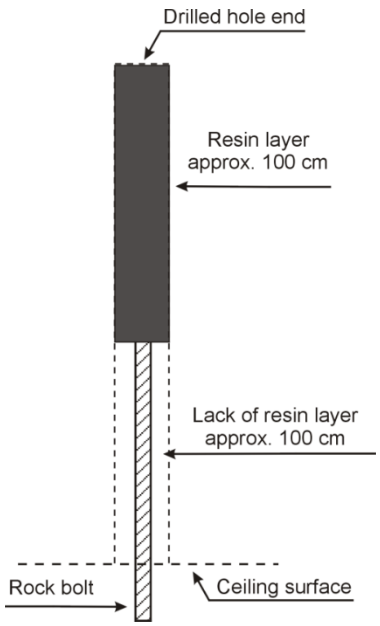


FIG. 3B: EXPERIMENTALLY EVALUATED DISCONTINUITY OF A RESIN LAYER FOR A GROUTED ROCK BOLT (ROCK BOLT LENGTH EQUALS 2m)

TABLE 1: COMPARISON OF IDENTIFIED NATURAL FREQUENCIES FOR A ROCK BOLT GROUTED AT ½ OF ITS LENGTH, STARTING FROM A REAR, HIDDEN END

No.	Frequencies, Hz	
	FEM	**Experiment**
1	89.3	90.5
2	250.8	247.8
3	492.8	475.8
4	816.5	780.9
5	1225.3	1147.4
6	1725.6	1596.7
7	2317.3	2118.5
8	2992.3	2702.6

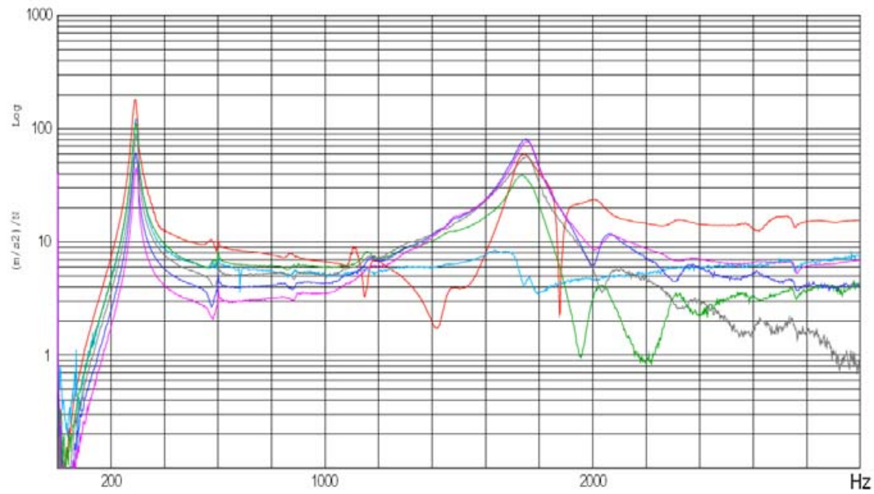


FIG. 4a: FRF CHARACTERISTICS OF DIFFERENT POINTS OF EXCITATION (MARKED WITH DIFFERENT COLORS) FOR A ROCK BOLT GROUTED ON ½ OF ITS LENGTH, STARTING FROM A CEILING SURFACE. AXIS X – FREQUENCY, AXIS Y – INERTANCE

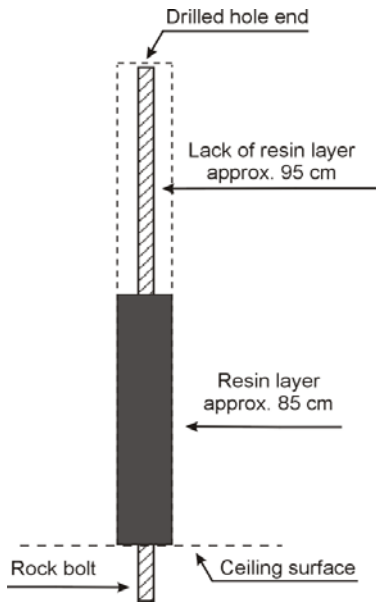


FIG. 4b: EXPERIMENTALLY EVALUATED DISCONTINUITY OF A RESIN LAYER FOR A GROUTED ROCK BOLT (ROCK BOLT LENGTH EQUALS 2m)

TABLE 2 COMPARISON OF IDENTIFIED NATURAL FREQUENCIES FOR A ROCK BOLT GROUTED ON ½ OF ITS LENGTH, STARTING FROM A CEILING SURFACE, FREQUENCIES MARKED WITH *) ARE CHARACTERISTIC OF NOT GROUTED, REAR PART OF A ROCK BOLT

No.	Frequencies, Hz	
	FEM	Experiment
1	98.9	-
2	277.1	-
3	307.9	306.9
4*)	544.3	585.2
5*)	903.2	924.4
6	1356.7	-
7	1815.1	1872.5
8	1909,1	-

Another trial to check the usefulness of the method was performed on cases where a discontinuity of the resin layer was located somewhere between the front and end part of the rock bolt. To check the validity of results, the process of grouting was divided into two stages: first the end part of a rock bolt and then the front one were grouted both with the known lengths. Figures 5a and 6a shows the measured FRF functions for such cases, and Figures 5b and 6b are graphical presentations of the determined discontinuities. The natural frequencies ω_r and damping ratios ξ_r for that cases are listed in Tables 3 and 4.

The damping ratio ξ_r is defined by (2):

$$\xi_r = \frac{c_r}{c_{cr}} \tag{2}$$

where:

c_r – damping corresponding to mode r

c_{cr} – critical damping corresponding to mode r

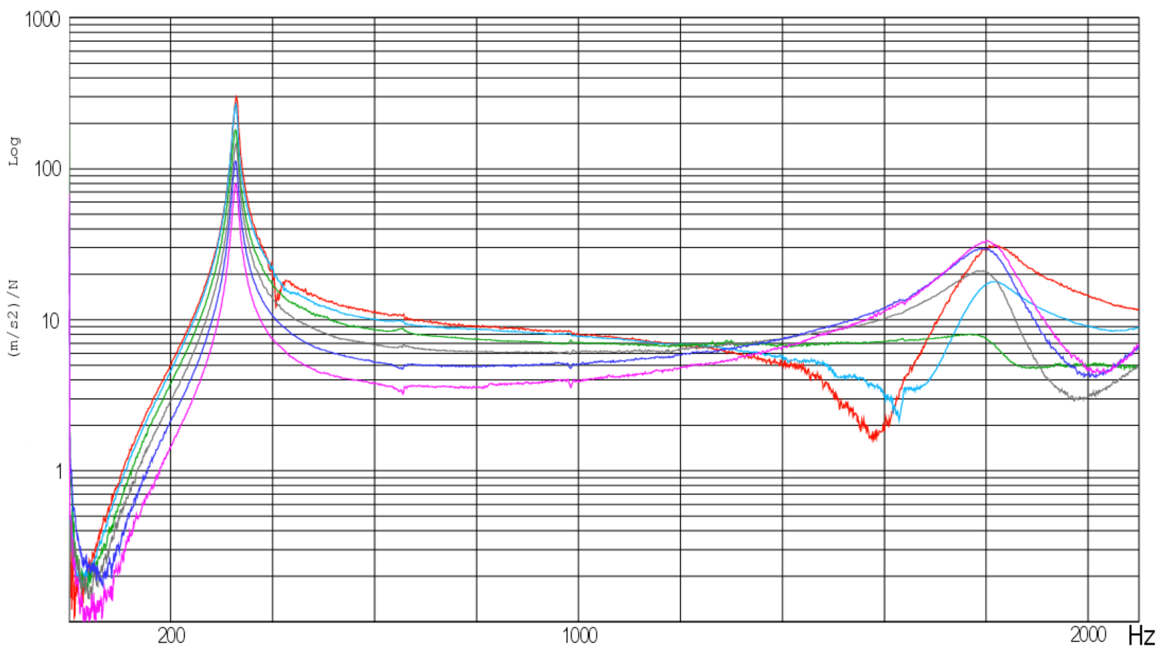


FIG. 5a: FRF CHARACTERISTICS OF DIFFERENT POINTS OF EXCITATION (MARKED WITH DIFFERENT COLORS) FOR AN ANALYZED CASE, LACK OF RESIN LAYER IN THE INNER PART OF A ROCK BOLT. AXIS X – FREQUENCY, AXIS Y – INERTANCE

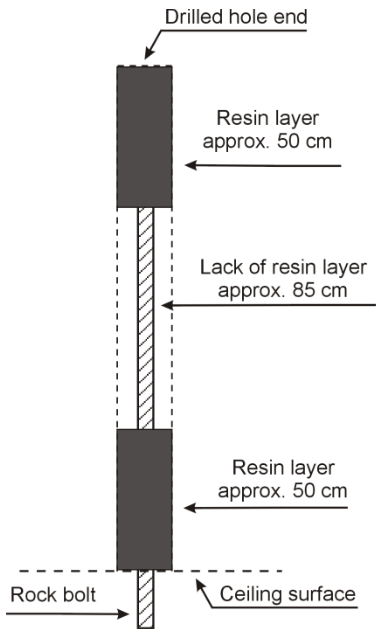


FIG. 5b: EXPERIMENTALLY EVALUATED DISCONTINUITY OF A RESIN LAYER FOR A GROUTED ROCK BOLT (ROCK BOLT LENGTH EQUALS 2m)

TABLE 3: IDENTIFIED NATURAL FREQUENCIES FOR A CASE, WHERE THE MIDDLE PART OF A ROCK BOLT IS NOT GROUTED, FREQUENCIES MARKED WITH *) ARE CHARACTERISTIC OF NOT GROUTED, INNER PART OF A ROCK BOLT

No.	Identified natural frequencies, Hz	Damping ratio, %
1	327.8	1.1
2*)	653.6	1.3
3*)	978.3	1.0
4*)	1634.9	0.6
5	1817.3	2.7

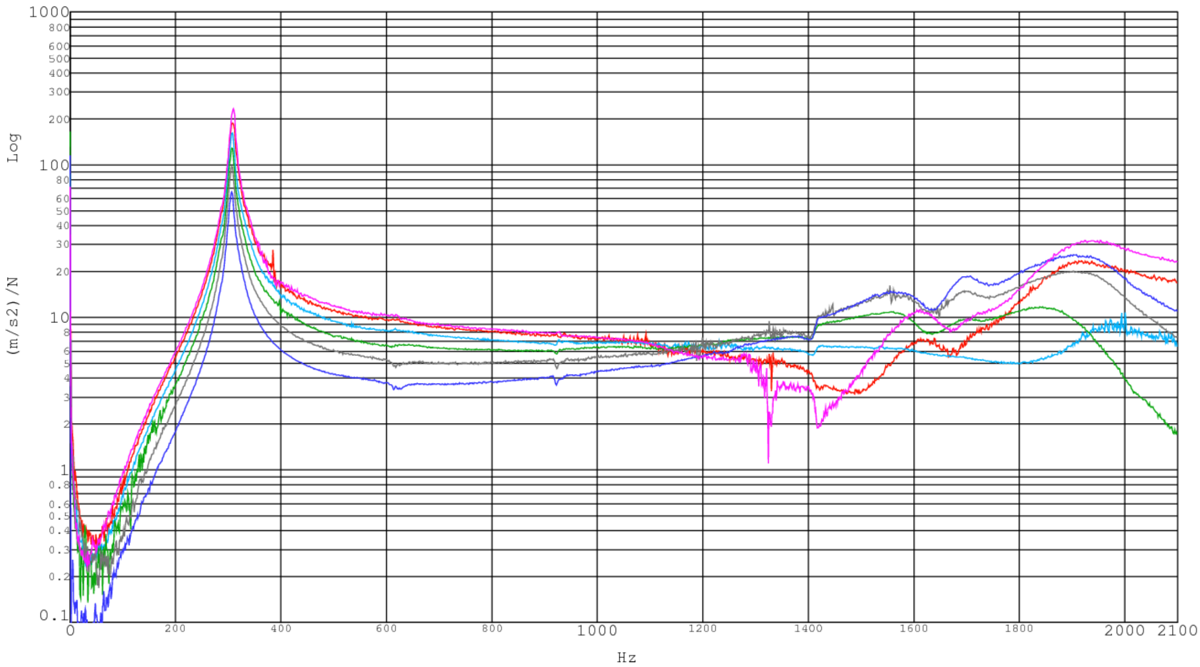


FIG. 6a: FRF CHARACTERISTICS OF DIFFERENT POINTS OF EXCITATION (MARKED WITH DIFFERENT COLORS) FOR AN ANALYZED CASE, LACK OF RESIN LAYER IN THE INNER PART OF A ROCK BOLT. AXIS X – FREQUENCY, AXIS Y – INERTANCE

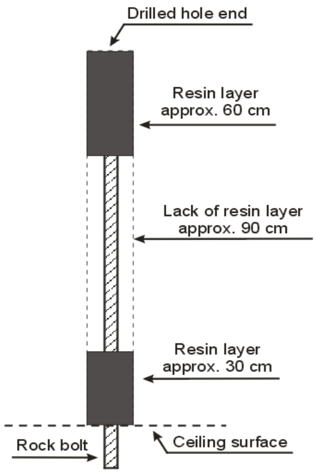


FIG. 6b: EXPERIMENTALLY EVALUATED DISCONTINUITY OF A RESIN LAYER FOR A GROUTED ROCK BOLT (ROCK BOLT LENGTH EQUALS 2m)

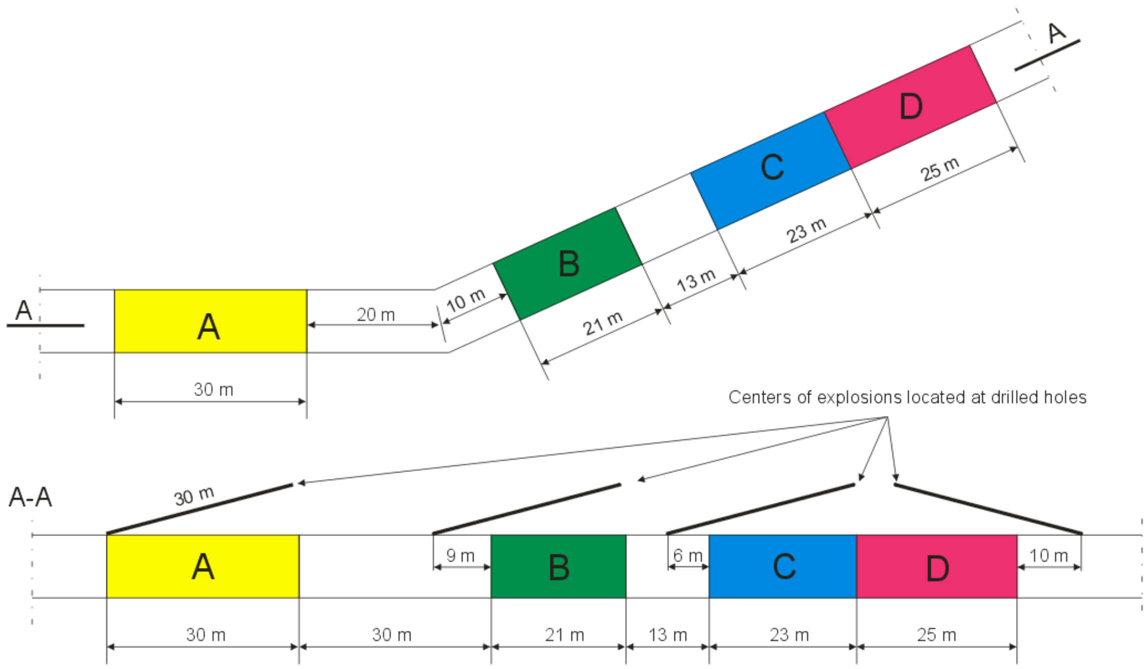
TABLE 4: IDENTIFIED NATURAL FREQUENCIES FOR A CASE, WHERE THE MIDDLE PART OF A ROCK BOLT IS NOT GROUTED, FREQUENCIES MARKED WITH *) ARE CHARACTERISTIC OF NOT GROUTED, INNER PART OF A ROCK BOLT

No.	Identified natural frequencies, Hz	Damping ratio, %
1	286.7	1. 6
2*)	571.0	1.5
3*)	859.5	0.4
4*)	1408.6	0.7
5	1493.5	3.5
6	1699.4	0.9

On the whole, the results were quite satisfactory. In-situ measurements showed that calculated damping might vary to a certain degree from sample to sample, thus reducing its utility. It can be incurred as a result of a conflict between the assumed damping behavior and that which actually occurs in reality, also the presence of small debris in the bore hole may influence the damping.

Research Work in the Coal Mine "JANKOWICE"

In accordance with other investigations on the subject, as Kidybinski [15] described, research on the effect of seismicity on continuity of the resin layer of grouted rock bolt was also undertaken. The investigated rock bolts were located in a coal mine roadway near the region of a blast site. The tests were performed before and after explosions. Centers of explosions were located at a distance of 5 to 10 meters from the rock bolts, shown on Figure 7. The loads of dynamite charge were as follows: part A: 30 kg, part B: 66 kg, part C: 60 kg, part D: 60 kg. As an assumption all the rock bolts were to be grouted on the whole lengths.



Part A: Arch supports
Part B: Rock bolt supports
Part C: Arch supports reinforced with rock bolts and steel net
Part D: Rock bolt supports reinforced with energy-absorbing bolts and steel net

FIG. 7: A SKETCH OF LOCATIONS OF CENTERS OF EXPLOSIONS IN AN INVESTIGATED OPENING

Figures 8a and 9a shows the example measured FRF functions before explosions, Figures 8b and 9b subsequently the measured FRF functions after explosions and Figures 8c and 9c are graphical presentations of the determined discontinuities and eventual changes. The natural frequencies for that cases are listed in Tables 5 and 6.

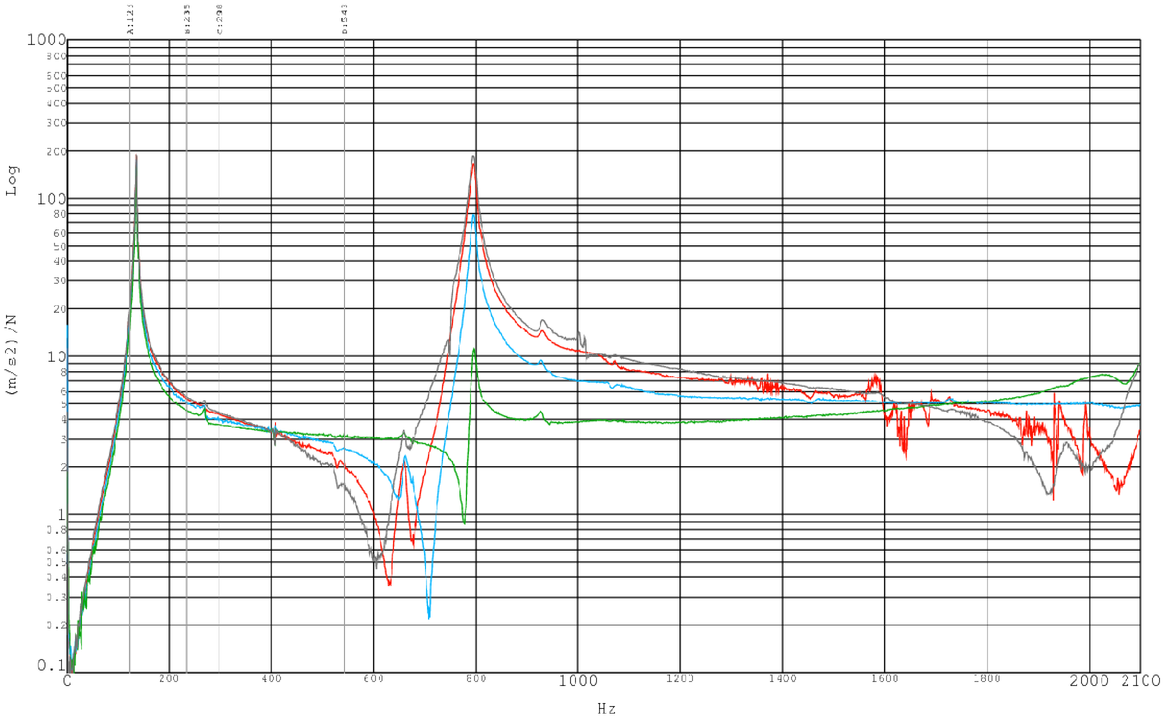


FIG. 8a: FRF CHARACTERISTICS OF DIFFERENT POINTS OF EXCITATION (MARKED WITH DIFFERENT COLORS) FOR AN ANALYZED CASE, BEFORE EXPLOSION. AXIS X – FREQUENCY, AXIS Y – INERTANCE.

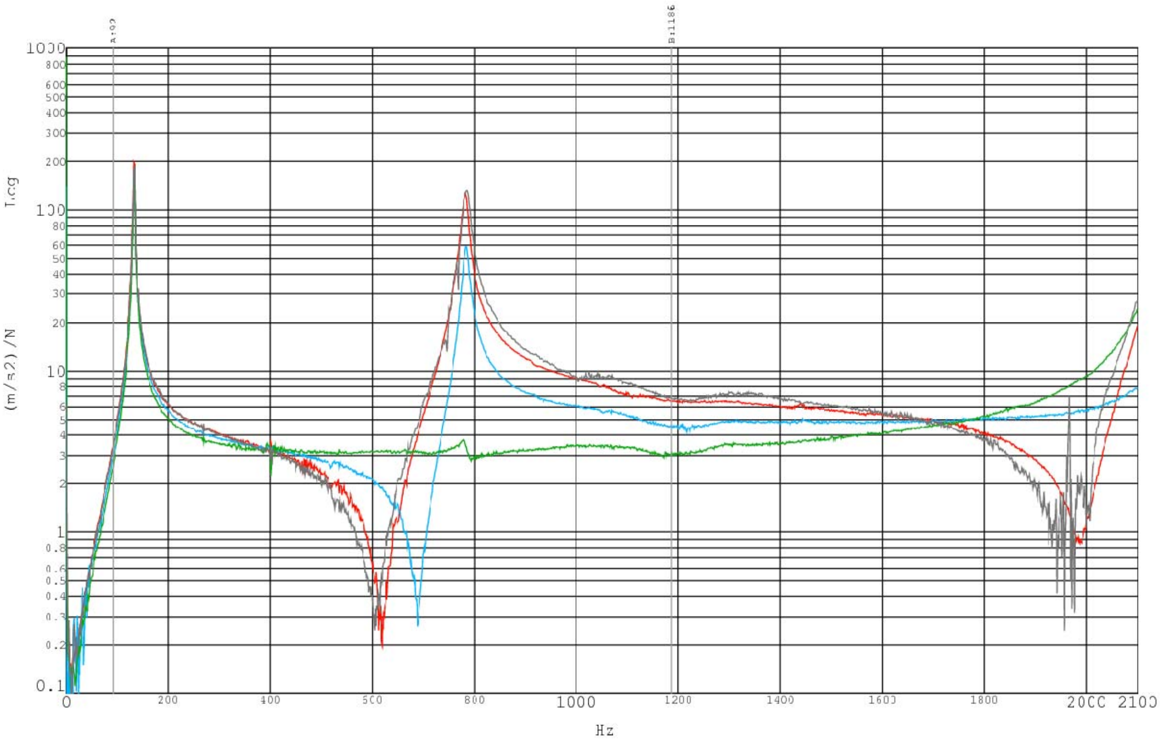


FIG. 8b: FRF CHARACTERISTICS OF DIFFERENT POINTS OF EXCITATION (MARKED WITH DIFFERENT COLORS) FOR AN ANALYZED CASE, AFTER EXPLOSION. AXIS X – FREQUENCY, AXIS Y – INERTANCE

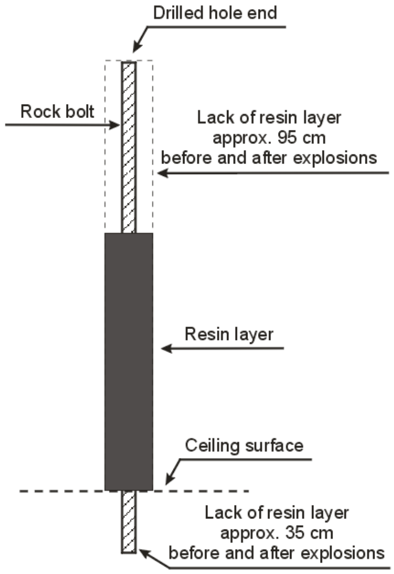


FIG. 8c: EXPERIMENTALLY EVALUATED DISCONTINUITY OF A RESIN LAYER FOR A GROUTED ROCK BOLT BEFORE AND AFTER EXPLOSION (ROCK BOLT LENGTH EQUALS 2.3m).

TABLE 5 IDENTIFIED NATURAL FREQUENCIES FOR A CASE, BEFORE AND AFTER EXPLOSION, FREQUENCIES MARKED WITH *) ARE CHARACTERISTIC OF NOT GROUTED, REAR PART OF A ROCK BOLT

Lp.	Identified natural frequencies before explosion, Hz		Identified natural frequencies after explosion, Hz
1	134.7	⇒	133.2
2*)	269.2	⇒	269.9
3	658.5	⇒	647.5
4	794.1	⇒	785
5*)	928.4	⇒	1011.4

The case analysed above was not fully grouted but no distinct changes were observed.

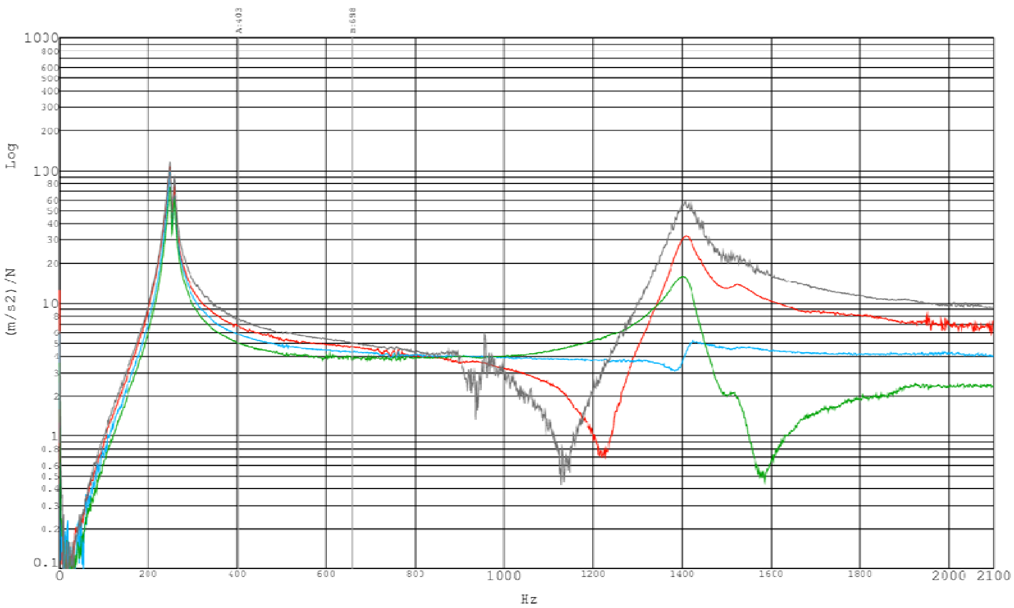


FIG. 9a: FRF CHARACTERISTICS OF DIFFERENT POINTS OF EXCITATION (MARKED WITH DIFFERENT COLORS) FOR AN ANALYZED CASE, BEFORE EXPLOSION. AXIS X – FREQUENCY, AXIS Y – INERTANCE

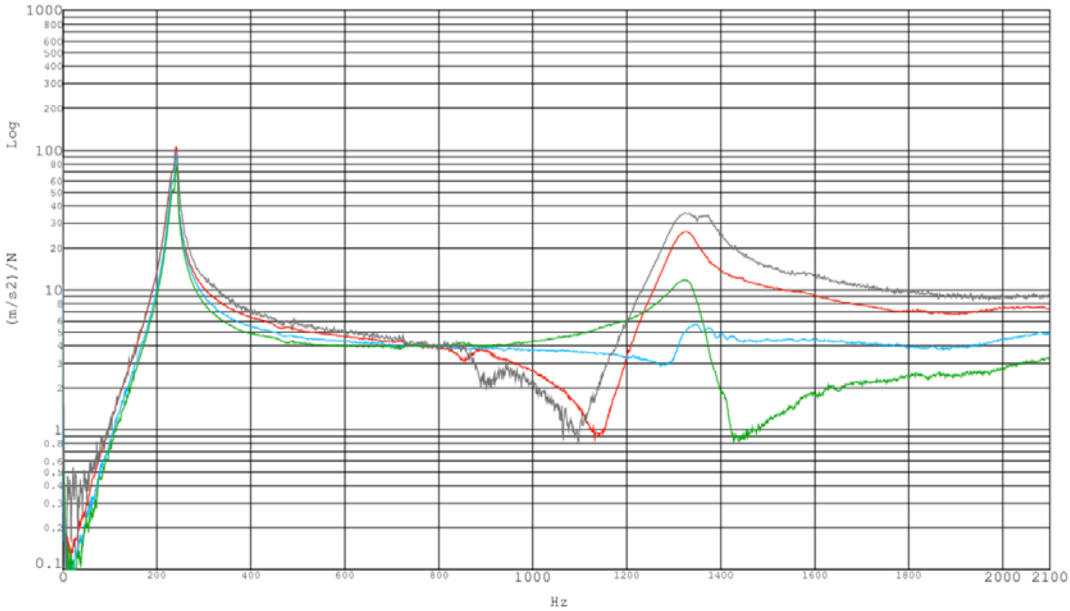


FIG. 9b: FRF CHARACTERISTICS OF DIFFERENT POINTS OF EXCITATION (MARKED WITH DIFFERENT COLORS) FOR AN ANALYZED CASE, AFTER EXPLOSION. AXIS X – FREQUENCY, AXIS Y – INERTANCE.

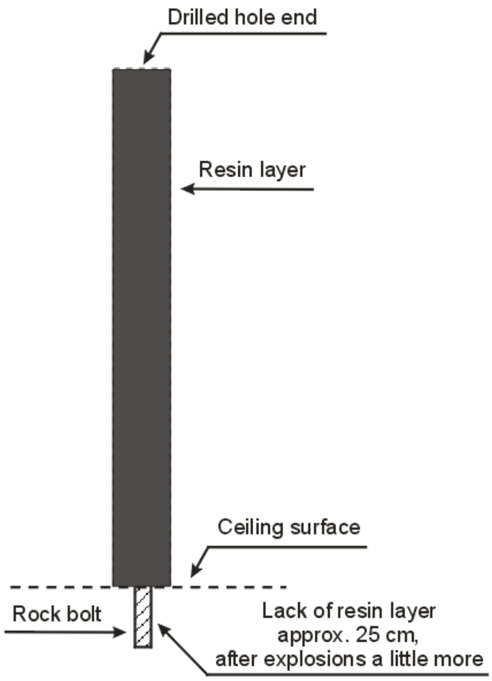


FIG. 9c: EXPERIMENTALLY EVALUATED DISCONTINUITY OF A RESIN LAYER FOR A GROUTED ROCK BOLT BEFORE AND AFTER EXPLOSION (ROCK BOLT LENGTH EQUALS 1.8m).

TABLE 6 IDENTIFIED NATURAL FREQUENCIES FOR A CASE, BEFORE AND AFTER EXPLOSION

Lp.	Identified natural frequencies before explosion, Hz		Identified natural frequencies after explosion, Hz
1	247.8	⇒	232.1
2	1406.9	⇒	1319.6

For the above case grout near the ceiling was slightly crumbled with the result of longer length of not grouted outer end.

The test results increased knowledge about the predicted behavior of a rock bolt support system when an explosion takes place in the near vicinity. Totally 18 cases were analyzed. In 10 cases there were no distinct changes in resin layer continuity (± 5cm). In 4 cases considerable deformation of rock bolts was recorded, which made the determination of a resin layer length impossible. In one case, the increase of stiffness of a rock bolt was observed, probably as a result of collapsing rocks, and the 3 remaining cases proved difficult to interpret.

Research Work in the Copper Mine "LUBIN"

Another test to check the usefulness of the method was a research work in a copper mine, where rock bolts in the roof strata had discontinuities known only to the staff of a mine department. After evaluating the discontinuities utilizing the method, the results were confronted with real, pre-set discontinuities. Twenty rock bolts were investigated in that experimental study. The results were quite satisfactory and proved the accuracy of the method as illustrated in Tables 7 and 8 and Figures 10a, 10b, 11a and 11b.

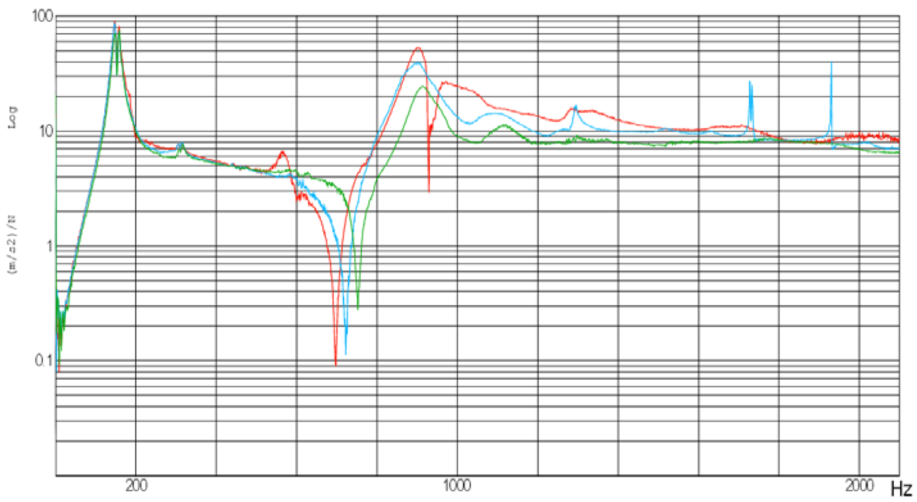


FIG. 10a: FRF CHARACTERISTICS OF DIFFERENT POINTS OF EXCITATION (MARKED WITH DIFFERENT COLORS) FOR AN ANALYZED CASE, METHOD VERIFICATION TRIAL. AXIS X – FREQUENCY, AXIS Y – INERTANCE.

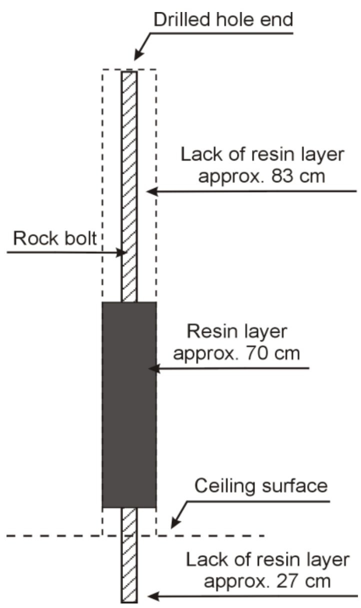


FIG. 10b: EXPERIMENTALLY EVALUATED DISCONTINUITY OF A RESIN LAYER OF A GROUTED ROCK BOLT WITH A VISIBLE LACK OF RESIN LAYER AT THE END PART OF A ROCK BOLT BEING DETERMINED AS THE MOST DANGEROUS CASE, METHOD VERIFICATION TRIAL (ROCK BOLT LENGTH EQUALS 1,8m).

TABLE 7 IDENTIFIED NATURAL FREQUENCIES FOR AN UNKNOWN CASE, METHOD VERIFICATION TRIAL, FREQUENCIES MARKED WITH *) ARE CHARACTERISTIC OF NOT GROUTED, REAR PART OF A ROCK BOLT

No.	Identified natural frequencies, Hz	Damping ratio, %
1	145.2	4.2
2*)	314.4	2.7
3*)	568.1	2.9
4	902.9	2.9
5*)	1290.6	0.6

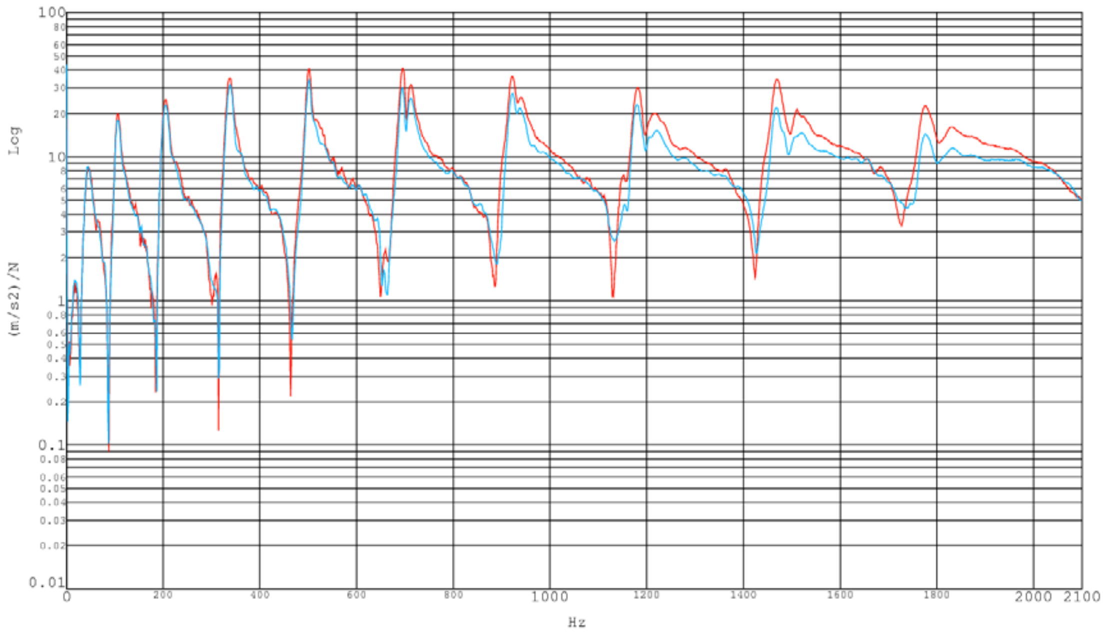


FIG. 11a: FRF CHARACTERISTICS OF DIFFERENT POINTS OF EXCITATION (MARKED WITH DIFFERENT COLORS) FOR AN ANALYZED CASE, METHOD VERIFICATION TRIAL. AXIS X – FREQUENCY, AXIS Y – INERTANCE.

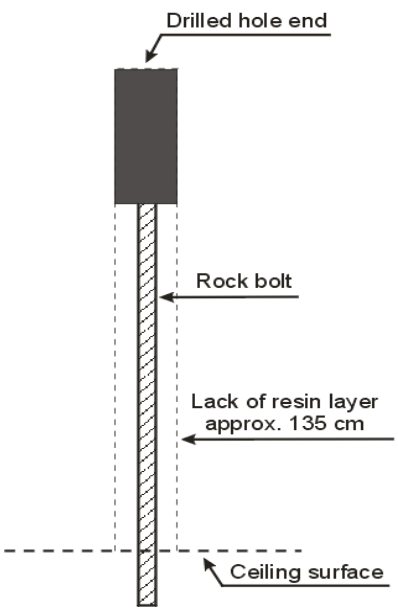


FIG. 11b: EXPERIMENTALLY EVALUATED DISCONTINUITY OF A RESIN LAYER OF A GROUTED ROCK BOLT, METHOD VERIFICATION TRIAL (ROCK BOLT LENGTH EQUALS 1,8m).

TABLE 8 IDENTIFIED NATURAL FREQUENCIES FOR AN UNKNOWN CASE, METHOD VERIFICATION TRIAL

No.	Identified natural frequencies, Hz	Damping ratio, %
1	43.8	13.4
2	105.3	3.7
3	205.2	2.4
4	337.6	1.9
5	500.2	0.8
6	693.7	0.7
7	919.7	1.1
8	1178.9	0.4
9	1468.6	0.6
10	1772.7	0.7

Conclusions

The developed method enables the identification of the length of discontinuity of grout in a rock bolt installation. It uses modal analysis procedures and is based on impact excitation and on reference of experimental modal model to the theoretical one. The advantages of the method include:

a. reliability of grouting discontinuity assessment on a continuous basis following installation,
b. a non-destructive character of the method,
c. the lack of necessity to install any additional equipment into a roof section.

Dynamic parameters of the tested structure (installed rock bolt) are determined by its boundary conditions, which are directly related to the length of grouting discontinuity. The dynamic measurement results support the assumption that boundary conditions are such that the in-situ bolt behaves like a cantilever. Of course not in all cases is the assumption fulfilled, i.e. the rock bolt is bent or cracked. It can be observed when the FRF function does not include distinguishable resonances and is quite different from typical characteristics (by typical we mean obtained by taking into account a very large number of investigated cases). To overcome this problem and determine that the rock bolt is not bent or destroyed by rock strata movement, ultrasonic guided waves ought to be used to check that there is no failure in inserted rock bolt (which should be straight and without any damage). That constitutes a limitation, but the main purpose of the method is to check the state of the grouting and not the state of rock bolt alone. Nevertheless, the apparatus was modified and equipped with an ultrasonic transducer.

Additional work is necessary to overcome problems with nonlinear behaviour of the analysed object, which resulted in a shift of relevant natural frequencies for theoretical vs. experimental models.

REFERENCES

[1] Li Charlie C.: "Principles of rock bolting in high stress rock masses", Mining & Environment, Vol. 2/1, pp. 133-143, Central Mining Institute, Poland, 2010.

[2] Tadollini S., C.: "Current roof bolting applications, technologies and theories in US mines", Mining & Environment, Vol. 2/1: 305-314, Central Mining Institute, Poland, (2010).

[3] Staniek A., Identification of Discontinuities in Resin Layer of Grouted Rock Bolts, Experimental Techniques, Vol. 36, No. 2, USA, 2012.

[4] The Complete ISRM (International Society for Rock Mechanics) Suggested Methods for Rock Characterization, Testing and Monitoring: 1974-2006. Editors: R. Ulusay, J.A. Hudson, Ankara, Turkey, 2007.

[5] European Standard EN 1936: 2006 Natural stone test methods – Determination of real density and apparent density, and of total and open porosity.

[6] Dossing O.: Structural Testing, Part II: Modal analysis and Simulation, Bruel & Kjaer, Denmark, 1988.

[7] Ewins D.J.: Modal Testing: theory, practice and application. Research Studies Press Ltd., England, 2000.

[8] Maia, N.M.M., Silva, J.M.M.: Theoretical and Experimental Modal Analysis, Research Studies Press Ltd., England, 1997.

[9] Uhl T.: Computer Aided Identification of Mechanical Models, WNT, Poland, 1997.
[10] Bishop R. H., Learning with LabVIEW, Prentice Hall, New Jersey, 2001.
[11] CADA-X User Manual, LMS, Lueven, 2000.
[12] Mechanical Vibration and Shock Measurements, Bruel & Kjaer handbook: 122-129, Naerum, 1982.
[13] Remington P. J.: Encyclopedia of Acoustics, Vol. 2, Ch. 63, 71, pp. 715-734, 843-855, John Wiley & Sons, New York,1997.
[14] Beard M.D., Lowe M.J.S.: Non-destructive testing of rock bolts using ultrasonic waves. International Journal of Rock Mechanics and Mining Sciences 40, pp. 527-536, 2003.
[15] Kidybiński A., Nierobisz A., Masny W.: "Maintenance of an opening affected by tremor enforced within nether roof strata", Proceedings of the Rockbursts 2005 Conference, 41-52, Central Mining Institute, Poland, 2005.